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A Younger Dryas signature in bison bone stable isotopes from the southern Plains of North America

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ABSTRACT

Stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope ratios from bison bone collagen recovered from Paleoindian bison kill sites provide a record of the B/A, YD, and EH climates in the North American southern Plains. This record is compared to the stable C isotopes derived from previously published, dated paleosols from the region. Together these data sources define a local response of the southern Plains grassland structure to the changing climatic conditions, specifically temperature and precipitation, during the Pleistocene/Holocene transition, including a Clovis drought and late Folsom warmup and drying.

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1. Introduction

The purpose of this study is to evaluate a possible indicator of the Younger Dryas (YD) environmental signature provided by stable carbon and nitrogen isotopes obtained from bison bone collagen from animals in late Pleistocene/early Holocene–age large-scale bison kill sites on the southern Plains of North America. Bison bone collagen isotopes provide a possible proxy measure of climate change for this region.

The Younger Dryas (YD) climate event is a 1300 calendar year span from 12,900 cal BP (12.9 ka) to 11,600 cal BP (11.6 ka) at the Pleistocene to the Holocene transition (Alley, 2000; Ballenger et al., 2011; Carlson, 2013; Rasmussen et al., 2006; Shakun and Carlson, 2010). During the period from ~12.9 to ~11.6 ka, the northern hemisphere experienced a climatic reversal of cooler temperatures following a post-Last Glacial Maximum (LGM) warming during the Bolling/Allerod (B/A; ~14.7–12.9 ka; Shakun and Carlson, 2010:1801). The reversal followed a gradient from low latitudes to high latitudes and was most pronounced in high latitude areas. Below ~35° latitude, the YD is variable in expression. Equatorial and southern hemisphere regions exhibit less pronounced climate change during this time (Carlson, 2013; Shakun and Carlson, 2010). Immediately following the YD, the climate in the northern hemisphere returned to the warmer pre-YD B/A conditions and continued to warm to the maximum highs that typify the inter-glacial maximum of the Altithermal ~8 ka (Shakun and Carlson, 2010:1802).

On the Plains of North America the YD is variably indicated. Below ~35° latitude the faunal record on the southern Plains records little to no change in temperature (Johnson, 1987; Toomey et al., 1993). Above ~35° latitude the YD is indicated in pollen records by an increase in *Artemesia* (Cummings, 1996) and, on the southern Plains in phytolith records by an increase in C_3 grasses following the pre-YD C_4 grass-dominated B/A and post-YD early Holocene (EH) (Bement et al., 2007a).

In many areas of the Plains the YD is marked by the formation of dark, organic-rich soils (Haynes, 2008). The thick paleosols dating to the YD interval suggest that an increase in precipitation or effective moisture accompanied by a drop in temperature. Together, the variables of temperature and precipitation influence the distribution of plant and animal communities (Johnson, 1987) that are then reflected in phytolith and stable isotopic signatures of soil organic matter (SOM) unless disturbance or alteration in the deposits occurs (Boutton, 1996; Fredlund and Tieszen, 1997; Wang et al., 2008).

A study of the grass phytoliths and stable carbon isotopes ($\delta^{13}C$) from dated buried soil A horizons within the Bull Creek drainage of the Oklahoma panhandle (~36.5° latitude), identified correlations between the percentage of warm season C_4 grasses and $\delta^{13}C$ values from SOM. During the period from ~14 ka to ~9 ka these variables trended from high percentages of C_4 grasses and enriched $\delta^{13}C$ values during the B/A to decreasing C_4 grasses and depleted $\delta^{13}C$ values during the YD, to a return to high levels of C_4 grasses and enriched $\delta^{13}C$ values

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during the EH and Altithermal (Bement and Carter, 2010; Bement et al., 2007a; Conley, 2010). To reiterate, the $\delta^{13}C$ values from SOM matched the C_4/C_3 grassland composition from phytolith analysis for each shift in temperature and precipitation level reflected during the time periods from B/A to YD to EH.

Ambrose and DeNiro (1986) and others (Julien et al., 2012) have shown a trophic level correlation between the $\delta^{13}C$ values of herbivore collagen and apatite fractions of bone and teeth and the vegetation they consume. On the North American Plains, the $\delta^{13}C$ of modern bison bone collagen and tooth enamel apatite has been shown to strongly correlate with latitudinal changes in modern grassland composition and the climate variables of temperature and precipitation (Chisholm et al., 1986; Hoppe et al., 2006; Julien et al., 2012; Lohse et al., 2014; Tieszen et al., 1998). In these studies, $\delta^{13}C$ from bison bone collagen and tooth apatite serve as proxies for grassland composition, temperature, and precipitation. These studies provide the basis to assess the hypothesis that the stable isotope composition from the large-scale bison kill animals from late Pleistocene through early Holocene age Paleoindian large-scale bison kill sites in northwest Oklahoma provide a proxy for changes in climate across these periods. To test for the presence of the YD paleoclimatic event using stable isotopes in faunal remains requires diachronic bison bone samples from a localized region.

The concentration of late Pleistocene through early Holocene age Paleoindian large-scale bison kill sites in northwest Oklahoma serve as an excellent source of bison bone for this study (Fig. 1). Bison samples bracketing and within the YD were available for study from the sites of Jake Bluff (34HP60), Cooper (34HP45), Badger Hole (34HP194), Jake Bluff East (34HP60-east), and Ravenscroft (34BV198).

This time period also marks the cultural shift from Clovis (13.3 ka–12.9 ka), during the waning centuries of the B/A, to Folsom (12.9 ka–12.2 ka), during the YD (Haynes, 1991; Holliday, 2000; Meltzer, 2006, 2009). Haynes (1991) identifies a Clovis-age drought followed by increasing effective moisture within the San Pedro River drainage of Arizona where a black mat demarcates the shift in climate. A similar shift is proposed across the Plains as indicated by widespread occurrences of YD-age black mats and dark organic-rich paleosols (Haynes, 2008). Although Holliday (2000), employing stable $\delta^{13}C$ isotopic analysis of buried soil A-Horizons from Southern High Plains draws and sand dunes, counters that the drought occurred during the Folsom period. Meltzer and Holliday (2010) argue that the low magnitude and slow pace of climate change during the YD may not have affected, or even been noticed by local inhabitants.

Given that soil $\delta^{13}C$ reflects the vegetation on that soil, vegetation $\delta^{13}C$ and $\delta^{15}N$ reflect temperature and precipitation levels, and that $\delta^{13}C$ of herbivore bone approximates the grassland biome in an area, we investigate the hypothesis that diachronic bison bone samples recovered from a discrete area will reflect changes in temperature and precipitation across the time period represented by the bison remains. Specifically, we investigate the proposition that bison bone collagen stable $\delta^{13}C$ and $\delta^{15}N$ isotopes from Paleoindian bison kill sites within the northwest Oklahoma portion of the southern Plains, USA, can be used to measure the intensity of environmental changes across the B/A, YD, and EH environmental transitions. In essence, we investigate the potential of bison bone $\delta^{13}C$ to serve as a proxy for climate change during this time period.

2. Methods

Bison bone samples were selected from large-scale kill sites along the 36th parallel of northwest Oklahoma. Amino acids from bone samples were extracted and purified at Penn State using a modified XAD technique described in Lohse et al., 2014 and Gilmour et al., 2015 (modified from Stafford et al., 1988, 1991). Starting weight for each sample was ~1 g given the highly degraded nature of the bone collagen in this region. Stable carbon ($\delta^{13}C_{collagen}$) and nitrogen ($\delta^{15}N_{collagen}$) isotope analyses were performed on the extracted and purified amino acids prior to AMS ^{14}C dating as a quality control measure. Carbon and nitrogen concentrations and stable isotope ratios were measured at the Yale Analytical and Stable Isotope Center with a Costech elemental analyzer (ECS 4010) and Thermo DeltaPlus analyzer. The reliability of the $\delta^{13}C_{collagen}$ results were ascertained by mass C:N ratios of each sample. Only samples with mass C:N ratios between the range found in modern herbivore bone (2.9 and 3.6) were combusted and sent to KCCAMS for graphitization and measurement. Sample CO_2 was then sent to KCCAMS (University of California, Irvine) where it was reduced to graphite at 550 °C using H2 and a Fe catalyst, with reaction water drawn off with Mg(ClO4)2 (Santos et al., 2004). Graphite samples were pressed into targets in Al boats and loaded on the target wheel for AMS analysis. ^{14}C ages were corrected for mass-dependent fractionation with measured $\delta^{13}C$ values (Stuiver and Polach, 1977), and compared with samples of Pleistocene whale bone (background, >48 ^{14}C kyr BP), late Holocene bison bone (~1850 ^{14}C BP), late AD 1800s cow bone, and OX-1 oxalic acid standards for calibration. Detailed descriptions of the

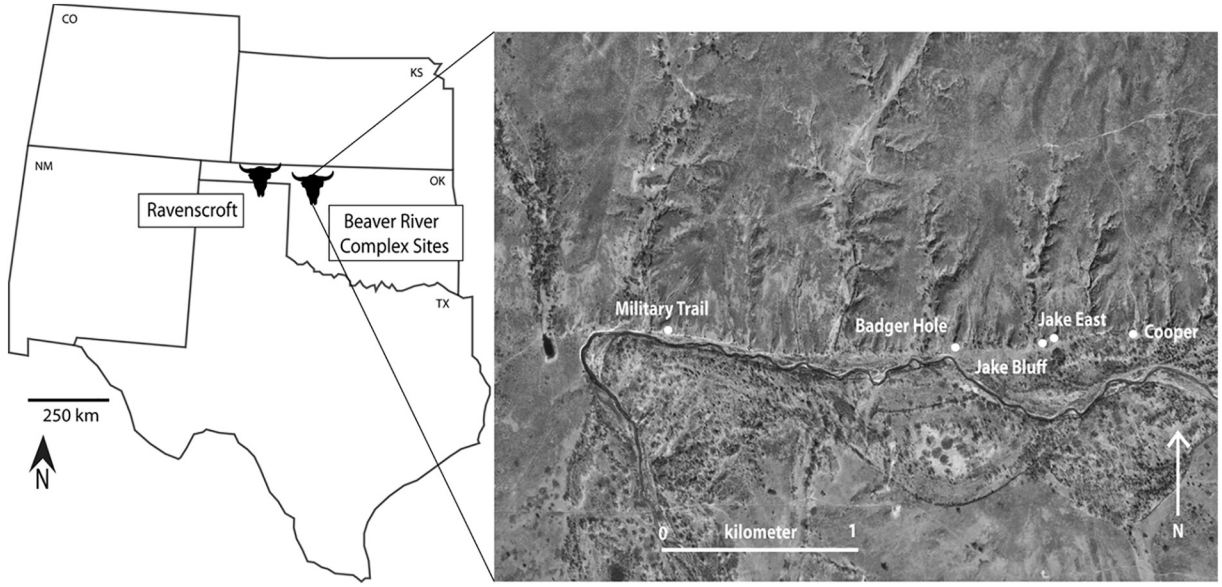

Fig. 1. The southern Plains area and location of the sites analyzed.

equipment used and analytical techniques employed can be found in Kennett et al., 2013; Lohse et al., 2014; and Hoggarth et al., 2014.

Multiple stable isotope samples representing different individuals were averaged to reconstruct environmental conditions and trophic level position. The $\delta^{13}C_{collagen}$ values were converted into percent C_3 grasses by the mass-balance equation (Carlson, 2015):

$$C_3(\%) = \left[\left(\delta^{13}C_{collagen} - 5.1_{\text{trophic level fractionation}} - \delta^{13}C_{C4}\right) / \left(\delta^{13}C_{C3} - \delta^{13}C_{C4}\right)\right] \times 100 \quad (1)$$

where $\delta^{13}C_{collagen}$ includes a 5.1‰ adjustment for trophic level fractionation (Kreuger and Sullivan, 1984), $\delta^{13}C_{C4} = -12.5‰$, and $\delta^{13}C_{C3} = -26.5‰$.

Percent C_4 by:

$$C_4(\%) = 100 - C_3(\%) \quad (2)$$

Mean annual temperature (MAT) was calculated from $\delta^{13}C_{collagen}$ by the equation provided by Lohse et al. (2014):

$$MAT_{collagen}\left(^{\circ}C\right) = \left[0.97 \times \left(\text{mean}\delta^{13}C_{collagen} + 10.1\right)\right] + 16.44 \quad (3)$$

where mean $\delta^{13}C_{collagen}$ requires a collagen-to-tooth enamel apatite offset of ~10.1‰ (Feranec, 2007) to approximate the $\delta^{13}C_{enamel}$ value used in the original equation developed by Hoppe et al. (2006). Values were rounded to the nearest °C.

Mean annual precipitation (MAP) was obtained by comparing $\delta^{15}N_{collagen}$ to the global tables provided by Schwarcz et al. (1999).

Bivariate plots of $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ by age (cal BP) provide the diachronic analyses.

3. Materials

The bison bone samples were selected from the Beaver River Complex of large-scale bison kills in Harper County, OK, the multiple kills at Ravenscroft from Beaver County, OK, and an isolated individual eroding from the Beaver River terrace near the Beaver River Complex sites (Fig. 1). The maximum distance between these localities is 115 km (70 miles) in east-west direction and range from 36.58 to 36.62° north latitude and 99.52 to 100.85° west longitude. Elevation across this area grades from a low of ~600 m amsl in the east to ~850 m amsl in the west. The sites are all contained within the Beaver River drainage and have been excavated within the last 20 years (Bement, 1999; Bement and Carter, 2010; Bement et al., 2012a; Bement et al., 2007b; Carlson et al., 2015).

The Military Trail site is a single articulated bison eroding from the late Pleistocene terrace of the Beaver River. The locality is 1.15 km (0.7 miles) upstream from the Beaver River Complex sites. The Jake Bluff site is the oldest of the Beaver River Complex large-scale bison kills (Bement and Carter, 2010). The skeletal remains of at least 22 cow/calf/juvenile bison were excavated from the floor of a dead-end arroyo (Fig. 2A). Four Clovis projectile points were recovered from the animal remains. The Cooper site, located 400 m downstream from the Jake Bluff site contains three large-scale arroyo trap bison kills (Bement, 1999; Fig. 2B). The three late summer/fall kills of cow/calf herds each contained 29, 29, and 20 animals associated with Folsom projectile points. The Badger Hole site is located 300 m upstream from the Jake Bluff site and contains the remains of a highly eroded arroyo kill of at least 12 bison associated with Folsom projectile points (Bement et al., 2012a; Fig. 2C). The Jake Bluff East site is an isolated bison processing pile located 50 m downstream from the Jake Bluff site (Carlson et al., 2015). Arroyos on either side of this processing pile have been flushed of their deposits, potentially removing the bison kill

Fig. 2. Examples of bone beds. A. Jake Bluff with Clovis point inset. B. Cooper site middle kill. C. Badger Hole bone bed. D. Ravenscroft II bone bed.

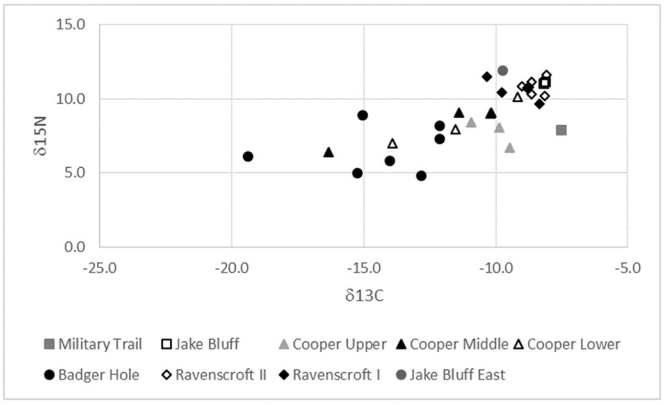

Fig. 3. Cross-plot of the $\delta^{13}C$ and $\delta^{15}N$ isotope results for each sample included in this analysis.

source of these bison bones. The final locality included in this analysis is the Ravenscroft site located in the Bull Creek drainage, a tributary of the Beaver River 115 km upstream (west) from the Beaver River Complex sites (Fig. 1). The Ravenscroft site consist of two adjacent arroyos, each containing bison bone concentrations along with cultural material (Bement et al., 2012b; Fig. 2D). The older of the kills, Ravenscroft II yielded a non-fluted lanceolate projectile point with characteristics crosscutting Plainview and Allen point styles.

4. Results and discussion

A total of 45 bison bone samples from 9 temporal assemblages were analyzed (SI Table 1). A total of 31 samples were sufficiently preserved for use in stable isotope analysis and 25 yielded radiocarbon assays based on the qualifying ratios discussed above. All radiocarbon results were calibrated using Calib 6.1 (Reimer et al., 2009) and are presented in calendar years before present (ka).

A cross-plot of the $\delta^{13}C$ and $\delta^{15}N$ isotopic results displays the overall variability in the data points (Fig. 3). Two main outliers occur within these groups; one for the Cooper middle kill and one for Badger Hole. Outliers can be the result of low collagen preservation not reflected by element yields or the C:N ratio; or may indicate that an animal originated in another physiographic region (Carlson, 2015; Meltzer, 2006:197). These outliers were removed from further consideration during this analysis.

As a group, the Beaver River Complex and Ravenscroft Paleoindian bison kills provide an age span from ~13.454 ka to ~10.209 ka, including the YD interval of 12.9 to 11.6 ka (Table 1; Alley, 2000; Rasmussen et al., 2006). The diachronic display of the $\delta^{13}C$ and $\delta^{15}N$ isotopic results is plotted along with the dated soil $\delta^{13}C_{SOM}$ results from soil A horizons within the Beaver River drainage (SI Tables 1 and 2; Conley, 2010), the GISP2 Ice Core results (Alley, 2000), the percent C_4 from phytolith analysis (Bement et al., 2007a), the $\delta^{13}C_{\text{tooth enamel}}$ (Zahrai, 2014), MAP estimates from $\delta^{15}N_{collagen}$, MAT from $\delta^{13}C_{collagen}$, and percent $C_{4collagen}$ (Fig. 4A-I).

The $\delta^{13}C_{collagen}$ results from the bison samples have enriched values immediately preceding the YD, depleted during the YD, and enriched again to near pre-YD levels in the early Holocene (Fig. 4F). The $\delta^{15}N$ values from the same bison bone samples display a similar trend. Changes in $\delta^{13}C_{collagen}$ relate to temperature and $\delta^{15}N_{collagen}$ indicate changes in mean annual precipitation (Lohse et al., 2014). Together, these values suggest climate shifted from relatively hot, wet conditions to hot, dry conditions immediately before the YD; changing to cool, moist conditions during the early YD; returning to hot, dry levels at the YD termination, and continuing hot and dry during the early Holocene (Fig. 4D, H). A recent study of bison tooth enamel from a subset of these sites displays a similar trend (Fig. 4E; Zahrai, 2014). Since the $\delta^{13}C$ and $\delta^{15}N$ composition of bison bone has been linked to the isotopic makeup of their diet. Low $\delta^{13}C$ values accompanied by low $\delta^{15}N$ indicates a diet of cool, moist-season C_3 grasses and forbs while higher $\delta^{13}C$ and $\delta^{15}N$ values indicate increasing levels of warm season drought resistant C_4 grasses (Hoppe et al., 2006; Julien et al., 2012; Lohse et al., 2014).

Bison are opportunistic grazers, meaning they ingest grasses in proportion to grass species abundance on the landscape (Lohse et al., 2014). Modern bison $\delta^{13}C$ values are highly correlated to the grassland composition breakdown between percent C_3 and C_4 of their rangeland (Hoppe et al., 2006; Tieszen et al., 1998). Application of Eqs. (1) and (2) (see Methods) to the $\delta^{13}C_{collagen}$ values provides the compositional breakdown of C_3 and C_4 grasses in bison diet within the study area (Table 1; Fig. 4G). Depleted $\delta^{13}C_{collagen}$ values are correlated with decreasing C_4 and increasing C_3 grass consumption. The trend in $\delta^{13}C_{collagen}$ values obtained from bison kills indicates this portion of the southern Plains had a high percent of C_4 grasses at the end of the B/A, followed by decreasing levels of C_4 grasses and increasing levels of C_3 grasses during the YD, and a return to high levels of C_4 grasses during the terminal YD and early Holocene.

When $\delta^{13}C_{collagen}$ was converted to °C (Eq. (3)) the trend shows that enriched $\delta^{13}C_{collagen}$ values correlate to higher temperature and depleted $\delta^{13}C_{collagen}$ values correlate to lower temperatures (Fig. 4H). The trend across the B/A, YD, and EH time period is one of relatively higher temperatures at the end of the B/A (~18 °C), lower temperatures during the YD (~12 °C), and a return to higher temperatures during the terminal YD and EH (~17 °C; Table 1).

To obtain information on possible changes in precipitation, the $\delta^{15}N_{collagen}$ was converted to precipitation estimates provided by the tables in Schwarcz et al. (1999). The result, plotted across time, shows that the B/A to terminal B/A sees a decrease in precipitation; followed

Table 1
Bison age, $\delta^{13}C$, $\delta^{15}N$, grassland composition, MAT, and MAP.

Locality	Mean 14C BP	α	Cal BP 2 α range of mean 14C BP[a]			Mean δ13C	Mean δ15N	%C3[b]	%C4[c]	MAT[d] °C	MAP mm/yr
			Min.	Median	Max.						
Ravenscroft I	9083	21	10,209	10,230	10,251	−8.9	10.6	10.7	89.3	18	100–200
Ravenscroft II	9338	21	10,496	10,545	10,594	−8.7	10.8	9.3	90.7	18	100–200
Jake East	10,020	35	11,322	11,488	11,654	−9.8	11.9	17.1	82.9	17	0–100
Badger Hole	10,347	16	12,066	12,145	12,224	−14.9	6.6	53.6	46.4	12	700–800
Cooper upper	10,532	19	12,422	12,503	12,583	−10.9	7.9	25	75	16	400–500
Cooper middle	10,563	19	12,522	12,569	12,616	−10.8	8.2	24.3	75.7	16	400–500
Cooper lowest	10,589	16	12,536	12,588	12,640	−10.7	8.3	23.6	76.4	16	400–500
Jake Bluff	10,821	17	12,590	12,712	12,833	−8.1	11.1	5	95	18	100–200
Military Trail	11,500	45	13,261	13,358	13,454	−7.5	7.9	0.7	99.3	19	400–500

[a] Calib 6.1.0; Reimer et al., 2009.
[b] Eq. (1).
[c] Eq. (2).
[d] Eq. (3).

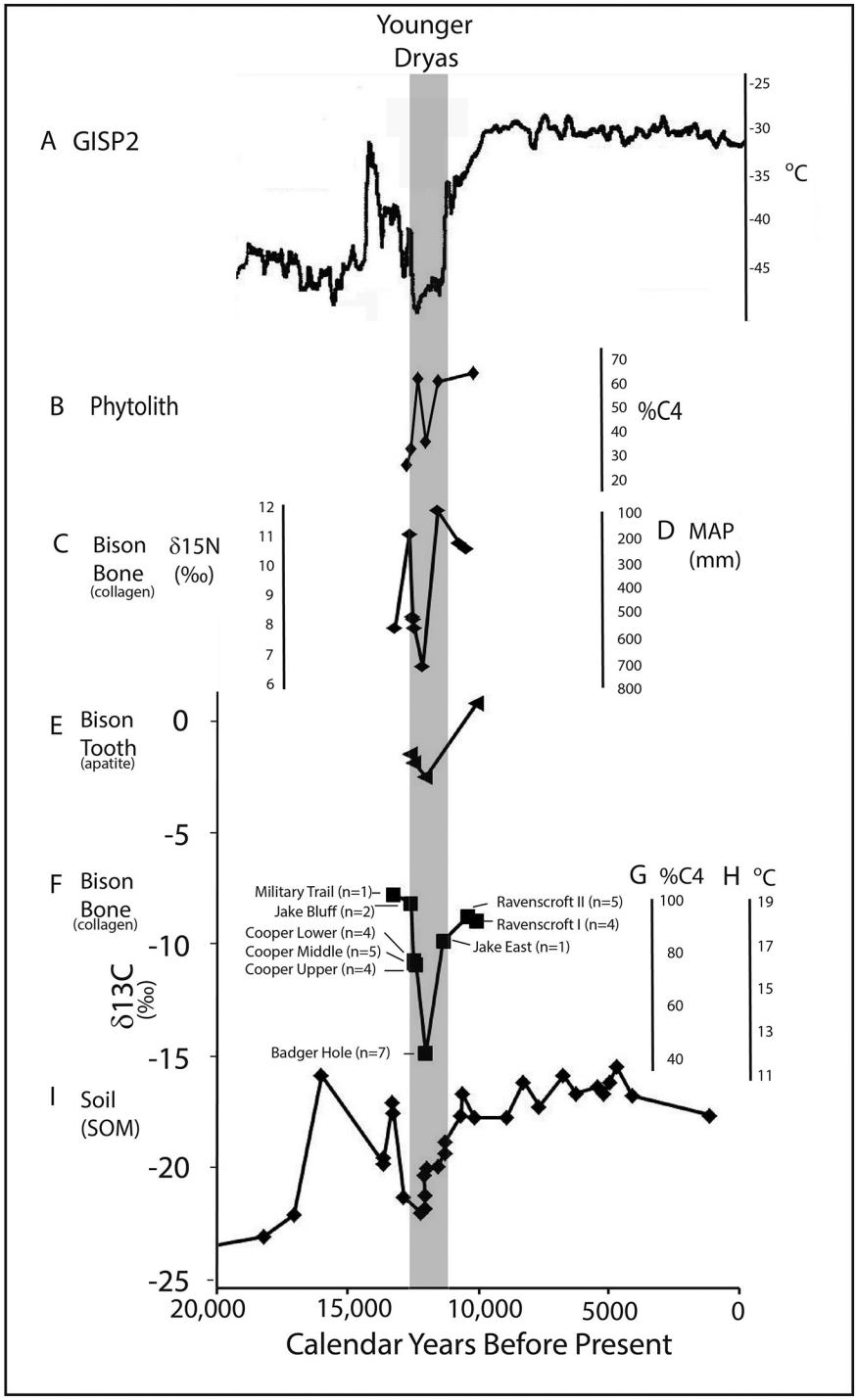

Fig. 4. Comparative YD curves are presented for A. GISP2 Ice Core (Alley, 2000), B. Percent C_4 from phytolith analysis (Bement et al., 2007a), *C. bison* bone $\delta^{15}N_{bone}$, D. MAP (mm/yr) estimated from $\delta^{15}N_{bone}$ (Schwarcz et al., 1999), *E. bison* tooth enamel $\delta^{13}C_{enamel}$ from Zahrai (2014), F. bison bones $\delta^{13}C_{bone}$, G. bison bone percent C_4, H. MAT (°C) from $\delta^{13}C_{bone}$, and I. mean cal BP dated Beaver River soil $\delta^{13}C_{SOM}$ (Conley, 2010). Shaded gray is duration of YD (12.9–11.6 ka).

by an increase in precipitation during the YD; and then a decrease in precipitation at the YD/EH transition, continuing into the EH to the Altithermal (Fig. 4D).

The results from the bison bones are compared to previously published records of climate change in this area. The bone isotope curves are similar to that displayed in the $\delta^{13}C_{SOM}$ curve obtained from dated stratified soil sequences within the Beaver River basin (Arauza et al., 2016; Conley, 2010; SI Table 2) The $\delta^{13}C_{SOM}$ values from these samples are consistent with decreasing temperatures and increasing precipitation or effective moisture regimes (Fig. 4I). Furthermore, increasing effective moisture levels are consistent with the development of rich soil A-horizons (Haynes, 2008). Paleovegetation reconstruction using $\delta^{13}C_{SOM}$ provides a high correlation between $\delta^{13}C_{SOM}$ and C_3/C_4 plant community composition (Wang et al., 2008). In these reconstructions, enriched $\delta^{13}C_{SOM}$ values correlate to higher C_4 grass composition, and depleted $\delta^{13}C_{SOM}$ values to lower C_4 grass composition.

As an additional analysis, the soils in the study area possess well-preserved phytolith records (Bement et al., 2007a). The phytolith record from samples associated with the soils dating across the YD provide a curve starting with an initial high C_4 (Chloridoid) percentage preceding

the YD, to decreasing C_4 and increasing C_3 (Festucoid) content during the YD, and increasing C_4 percentages at the terminal YD and EH (Fig. 4B).

A comparison of the percent C_3/C_4 composition of the grasslands through time obtained from the phytolith study and that obtained from the bison bone data show similarities but also some important differences. The overall trends between the two datasets are similar, displaying increased C_3 grass composition at the height of the YD ~12.145 ka and dominance of C_4 grasses preceding and after the YD. The differences are found in the magnitude or scale of changes in grassland composition. The bison bone samples range from a high of 100% C_4 grasses before the YD to 45% at the height of the YD. The phytolith records for these time periods display highs and lows of 60 and 30%, respectively. Several factors may account for these discrepancies of scale. First, the bone and phytolith samples are not from contemporaneous sources. All phytolith records are from the dated soil sequences along Bull Creek (Bement et al., 2007a) and the Bull Creek sequence does not match the ages exactly of the kill sites. Annual, decadal, or centennial shifts in grassland production could be responsible for the discrepancies in results.

None of the sediment enveloping bison bones were included in this study because bison kill sites may be over-influenced by seasonally-specific bison gut pile contents rather than multi-season annual grassland production (Bement, 2009). This is a particularly important distinction in areas such as the southern Plains where seasonal grassland composition varies substantially between spring and fall cool-season C_3 grasses and summer warm-season C_4 grasses. Since bison are non-selective (opportunistic) grazers, their gut content will contain the proportions of C_3 and C_4 grasses consistent with the season of kill. Hence a summer kill deposit (which all the Beaver River Complex kills are) will contain higher C_4 phytolith levels than a cool season (spring or autumn) kill. Sediments from these sites will contain an over-abundance of C_4 phytoliths. Another source for the discordance between these two records may relate to niche differences between the upland interfluves where bison predominantly graze and the streamside terrace location of the soil phytolith sources (Rosas et al., 2005).

5. Conclusion

The use of stable $\delta^{13}C$ and $\delta^{15}N$ isotopes from bison bones to reconstruct the environment across the B/A, YD, and EH boundaries identified trends documented by previously published soil stable isotopes and phytolith records for the same NW Oklahoma area. The bison bone $\delta^{13}C$ results follow the trends in phytolith recovery from soils, and the $\delta^{13}C_{SOM}$ to define shifts in climate that are concordant with a cooling of climate during the YD on this portion of the southern Plains. The $\delta^{13}C$ and $\delta^{15}N$ values from dated bison bone collagen allow reconstruction of the temperature and precipitation, respectively. Acting independently, these variables depict the warm, wet climate shifting to warm, dry conditions immediately preceding the YD, and then dropping to cold, wet conditions during the majority of the YD. The end of the YD witnessed warming and drying conditions emerging into the EH's hot, dry climate. The results of the bison bone stable $\delta^{13}C$ and $\delta^{15}N$ analysis support the occurrence of a Clovis-age drought immediately preceding the YD and development of the Folsom culture. The results also indicate a terminal YD warm dry peak that ameliorated slightly and continued into the EH. The temporal resolution provided by the bison samples utilized in this study was not sufficient to assess the hypothesis that human groups living in the area may or may not have noticed the change in climate conditions. The results do, however, tend to support the patterns described by Shakun and Carlson (2010) that above 35° latitude the YD signal is stronger compared to its expression below 35° latitude. On the North American southern Plains, the YD temperature below 35° latitude declined between ~1 to 3 °C (Johnson, 1987; Toomey et al., 1993) compared to the ~6 °C decline in temperature in our study area above 35° latitude. The effect of this steep temperature gradient on the people and fauna in this portion of the southern Plains is a topic for future investigation. For now, the bison bone isotopic record from Beaver River basin sites provides an additional proxy for paleo-environmental reconstructions on the Plains of North America.

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